Experimental Investigations of a Selective Weakening Approach for the Seismic Retrofit of R.C. Walls

M.G. Ireland, S. Pampanin & D.K Bull

Department of Civil Engineering, University of Canterbury, Christchurch.

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ABSTRACT: Current seismic retrofit strategies generally focus on increasing the strength/stiffness or upgrading the mechanical properties of a structure or element. A typical drawback of this approach is that the demand on structural and sub-structural elements can be increased. In a previous contribution by the authors (Ireland et al., 2006) a counter-intuitive but rational seismic retrofit strategy consisting of selective weakening techniques was proposed.

In this paper results of experimental investigations performed on benchmark & selectively weakened structural walls at the University of Canterbury are discussed. The experimental investigations consisted of quasi-static uni-directional tests on two benchmark and two retrofitted cantilever wall specimens. The first benchmark wall specimen was detailed as typical of pre-1970's construction practice. An equivalent wall was retrofitted using a selective weakening approach involving a horizontal cut at foundation level to allow for a controlled rocking response. The second benchmark specimen represented a more severe scenario where the inelastic behaviour was dominated by shear. A retrofit solution involving vertically segmenting the wall to improve the ductility and retain gravity carrying capacity by inducing a flexural response was implemented.

The experimental results confirmed the viability and efficiency of the proposed retrofit technique towards improving the performance of structural walls. Constructability issues and suggestions for practical implementation of the proposed retrofit solution are also discussed.

1 INTRODUCTION

A selective weakening approach for seismic retrofit was introduced and investigated in a previous contribution by the authors (Ireland et al., 2006). Selective weakening focuses on strategically weakening specific elements within a structure to alter the inelastic mechanism and to protect other elements within the structure (i.e. foundations) (Pampanin, 2006). After the initial weakening is performed other currently available retrofit techniques (i.e. FRP or post-tensioning) will have to be incorporated into the retrofit solution to ensure that the principles of capacity design are met and a targeted performance level is achieved. Preliminary suggestions regarding the use of strategic weakening to improve the performance of a structure can be found in FEMA-273 (FEMA, 1997), FEMA-356 (FEMA, 2000) and more recently in the NZSEE Guidelines for the "Assessment and Improvement of the Structural Performance of Buildings in Earthquake" (NZSEE, 2005). Additionally selective weakening techniques can be used to introduce behavioural characteristics associated with recently developed high performance seismic resisting system (hybrid) to an existing structure (Priestley, 1991; Priestely et al., 1999). The characteristics include a rocking re-centring behaviour that exhibits minimal damage after a cyclic response.

This paper provides a brief overview of the results of experimental investigations that were performed to conceptually assess the feasibility and viability of using selective weakening techniques to improve the cyclic performance of reinforced concrete structural walls (Ireland, 2007). Quasi-static cyclic uni-directional in-plane testing was performed on two benchmark and two retrofitted, 2/3 scale, cantilever wall specimens that represented the base portion of a prototype structural wall.

2 THE CONCEPT OF SELECTIVE WEAKENING

Current seismic retrofit strategies generally focus on increasing to capacity of individual elements within a structure or the structure as a whole (e.g. concrete jacketing). A disadvantage of this approach is that the demand of the structural and sub-structural elements can be increased. Selective weakening, which focuses on initially disconnecting structural elements to improve the performance offers the following advantages: (a) ability to reduce or control the demand of the foundation by controlling the capacity of the wall; (b) introduce capacity design principles by changing inelastic mechanism from shear to flexure; (c) avoid potential for longitudinal reinforcement buckling (due to large spacing of transverse reinforcement typical in existing walls) and the possibility of a lap splice failure by using a horizontal cut at foundation level; (d) reduce the damage associated with the development of a plastic hinge by introducing a rocking behaviour; (e) introduce a rocking re-centring behaviour through the use of balanced contributions of mild steel reinforcement and un-bonded post-tensioning.

Figure 1 shows a variety of selective weakening solutions that could be used to modify the behaviour of an existing poorly performing structural wall or to preserve the foundation from undesired damage and collapse. Figure 1(a) shows a poorly detailed as-built wall, which has a shear dominated inelastic mechanism and substantial strength degradation can be observed in the hysteretic response. Figure 1(b) shows two possible “partial” selective weakening solutions which can be used to modify the response of the existing wall. Wall (b’) has been segmented by a vertical cut, which lowers the flexural capacity and therefore the shear demand. The contribution to the seismic resisting system would be reduced but substantial strength degradation could be avoided, to ensure that the wall is capable of providing reliable gravity carrying capacity after a cyclic response. Due to the vertical cut severing the transverse reinforcement the shear capacity would have to be reinstated (FRP wrapping could be a possible solution). Wall (b’’) has been selectively weakened using a horizontal cut at foundation level. The cut severs all the longitudinal reinforcement, lowering the flexural capacity and avoiding a shear failure. This introduces a rocking behaviour, with a bilinear-elastic hysteretic response.

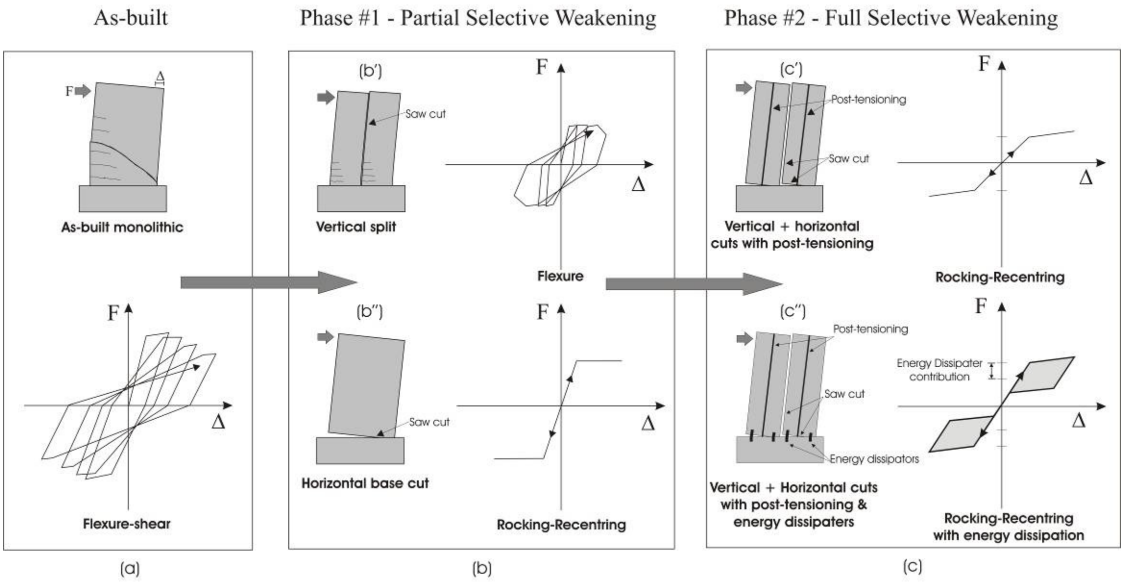


Figure 1: Expected behaviour and hysteretic response of a wall before and after the implementation of different selective weakening solutions: (a) as-built wall; (b) initial weakening; (c) complete selective weakening solution

Figure 1(c) shows two “full” selective weakening retrofit solutions which involve an initial weakening and then the use of additional already available retrofit techniques to improve the performance. The initial weakening involves vertically segmenting the wall and horizontally cutting it at foundation level. Wall (c’) involves the initially weakening with the addition of un-bonded post-tensioning to increase the flexural capacity and control the rocking response. Wall (c'') takes the solution a step further and in addition to the initial weakening and the use of un-bonded post-tensioning, energy dissipation devices are added to increase the flexural capacity and provide energy dissipation to reduce the displacements experience during a seismic response. The energy dissipation devices can be as simple as mild steel reinforcement. Through using a balanced contribution of post-tensioning and energy dissipaters a rocking re-centring behaviour (no residual displacements) can be achieved, with a flag-shaped hysteretic response experienced. This gives the retrofitted wall the characteristics of recently developed high performance seismic resisting systems based on the ductile jointed (hybrid) connection (Priestley, 1991; Priestley et al., 1999).

3 POSSIBLE SELECTIVE WEAKENING RETROFIT SCENARIOS

The effect of selective weakening on the monotonic force versus displacement response, with consideration of the foundation capacity, for three different scenarios is shown in Figure 2. The force versus displacement response for the existing as-built wall, a concrete jacket retrofit solution and a partial selective weakening technique are shown in Figure 2 (a). The existing wall exhibits a non-ductile response, whilst the concrete jacketing retrofit results in an increase in the strength/stiffness, which in turn results in the foundation capacity being exceeded. Alternatively a partial selective weakening technique (which involves vertically segmenting the wall) could be used, this would result in a substantially lower flexural capacity, but this would ensure that the foundation capacity would not be exceeded and that the displacement capacity would be increased.

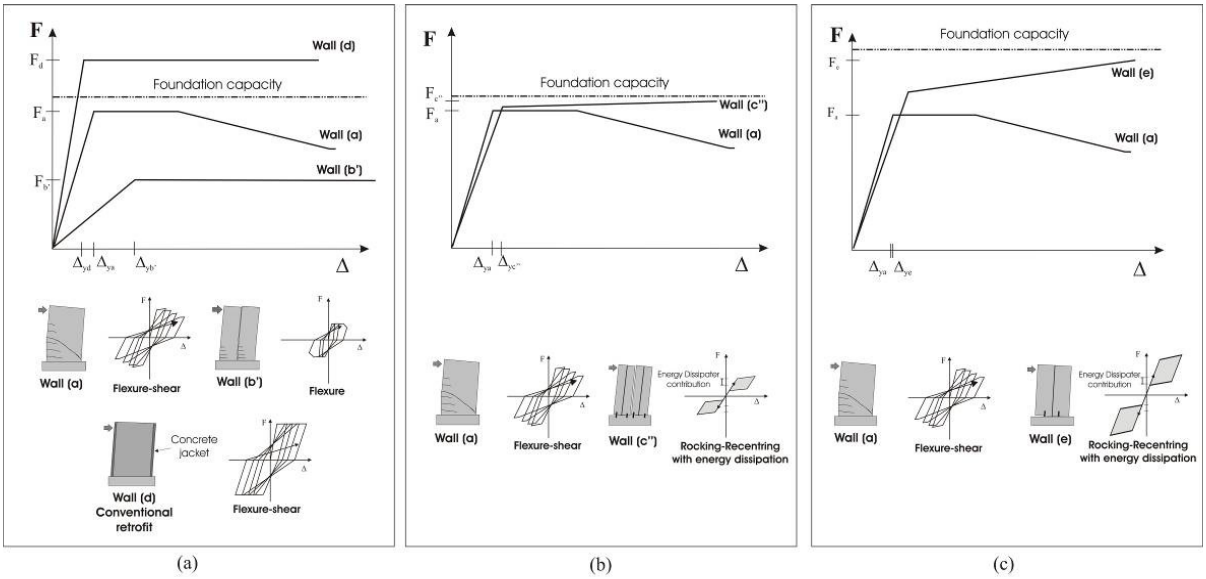


Figure 2: Selective weakening capacity design consideration

Figure 2 (b) shows the force versus displacement response for an existing wall and a full selective weakening retrofit solution (wall (c'), where the retrofitted walls capacity is targeted to be just below the capacity of the foundation. The selective weakening solution involves vertically segmenting the wall as well as horizontally cutting it at foundation level. In addition un-bonded post-tensioning and energy dissipaters are used, which will introduce the characteristics of a hybrid system. This maximises the lateral load carrying capacity that can be achieved from the wall without exceeding the foundation capacity. However during seismic response it would be expected that the fully selectively weakened wall would experience higher peak displacements than a monolithic wall of equivalent strength, as the flag-shaped hysteresis will result in a lower level of energy dissipation.

Figure 2 (c) shows a situation where the foundation capacity is not critical but retrofit is required to improve the displacement capacity of the existing wall. A selective weakening solution which aims to improve the displacement capacity and reduce the peak displacements experienced during seismic response is shown as wall (e). The selective weakening retrofit solution consists of a horizontal cut at foundation level to induce a rocking response, along with a combination of un-bonded post-tensioning to introduce a self-centring behaviour and energy dissipaters to reduce the displacement demand. In order to achieve a lower peak displacement using the selective weakening solution, the strength of the retrofitted wall would have to be greater than that of the as-built wall (due to lower energy dissipation). This solution would only be suitable in situations where foundation capacity is adequate.

4 EXPERIEMENTAL INVESTIGATIONS

A series of experimental tests were performed to investigate the feasibility and viability of using selective weakening techniques for the seismic retrofit of reinforced concrete structural walls. A total of four tests were performed on two benchmark (W1 & W2) and two retrofitted (W1R & W2R) wall specimens. Quasi-static cyclic uni-directional testing was performed on the cantilever wall specimens, which were 2/3 scale and represented the base portion of a prototype structural wall.

W1 was the first benchmark specimen and was designed and constructed to represent a typical pre-1970's New Zealand structural wall. This included plain round reinforcement with a straight lap splice detail at the base of the wall, the full details can be seen in Figure 3. W1R was the retrofitted equivalent of W1. The retrofit solution adopted used a selective weakening technique involving a horizontal cut at foundation level, severing all the longitudinal reinforcement and inducing a rocking behaviour. Through the use of balanced contributions of un-bonded post-tensioning and energy dissipaters characteristics similar to a hybrid system were achieved (including rocking re-centring and minimal damage). The retrofit solution represents a scenario similar to that outlined in Figure 2 (c), where the aim is to improve the displacement capacity, introduce characteristics common of recently developed high performance seismic resisting systems and to minimise the displacements experienced. The retrofit configuration and components for W1R are shown in Figure 4.

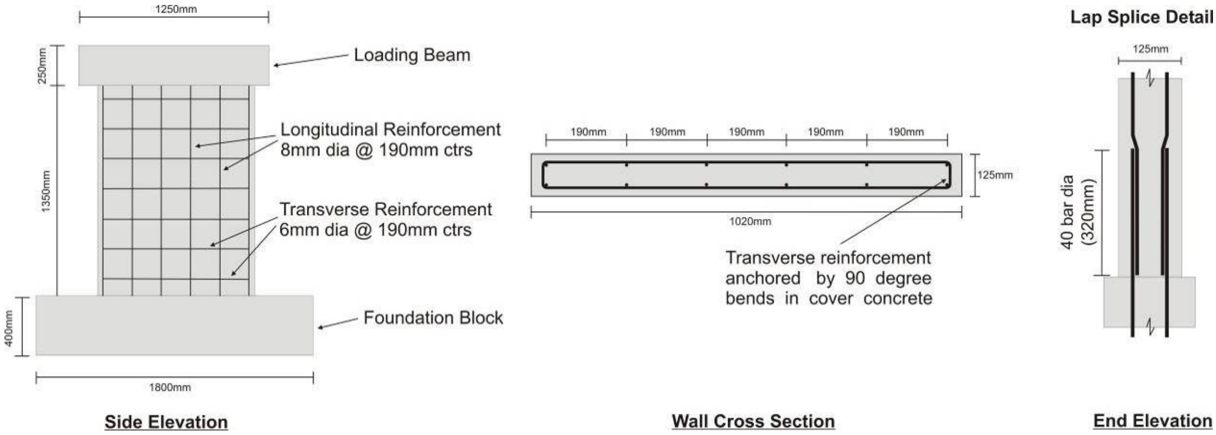


Figure 3: W1 reinforcement details and geometry

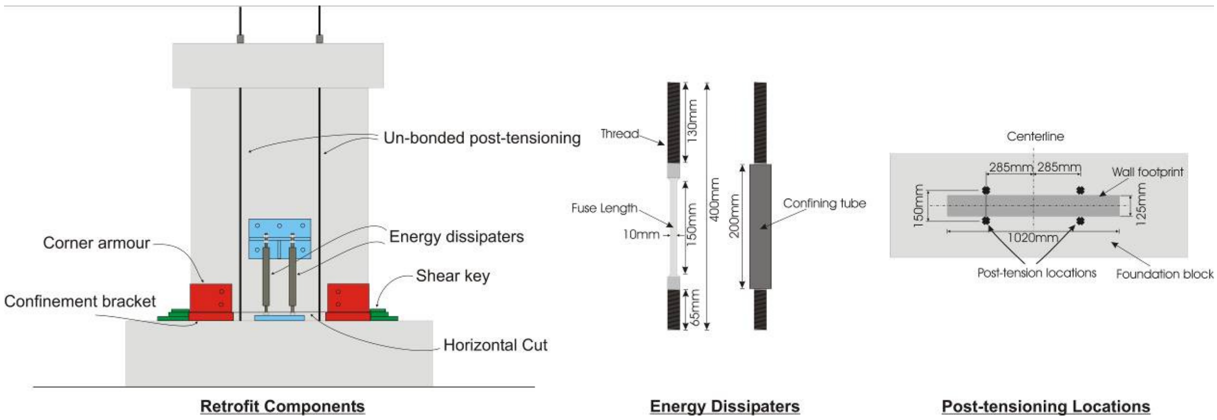


Figure 4: W1R retrofit components

W2 was the second benchmark specimen, which represented a severe scenario where the wall was dominated by shear. The wall was reinforced with a large quantity of boundary element reinforcement, within the rectangular cross-section of the wall, the reinforcement details can be seen in Figure 5. W2R was the retrofitted equivalent of W2. The retrofit solution implemented involved vertically segmenting the wall, with the aim of improving the displacement capacity by introducing a flexural response and to ensure that the gravity carrying capacity was maintained after a cyclic response. In one of the two wall segments a 100mm horizontal saw cut was used to partially sever the boundary element reinforcement. This involved severing 2-HD16's and 2-HD12's of the boundary element and was used to ensure a ductile flexural response was achieved. The horizontal cut was only applied to one of the wall segments so that the effects of the horizontal cut could be monitored. To reinstate the shear capacity after the wall was vertically segmented FRP bands were used. Steel confinement armour was also used at the base of the wall to prevent crushing and spalling. The retrofit configuration and components can be seen in Figure 6.

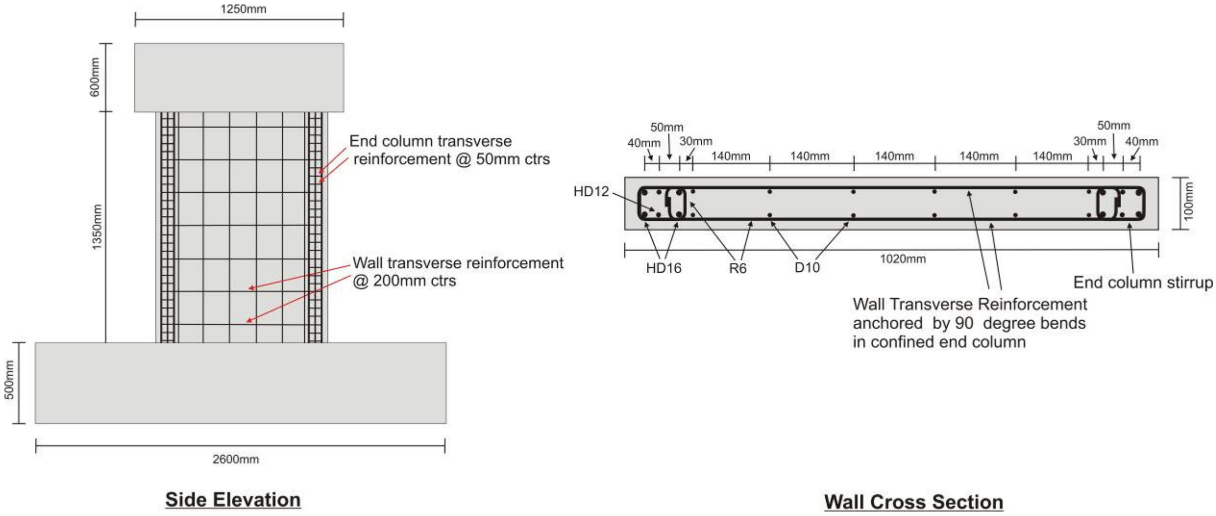
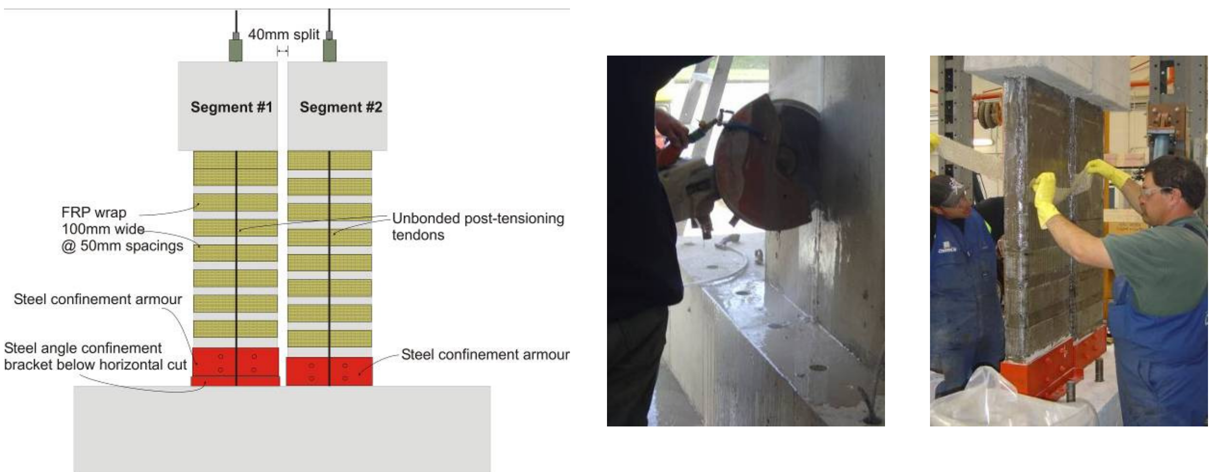


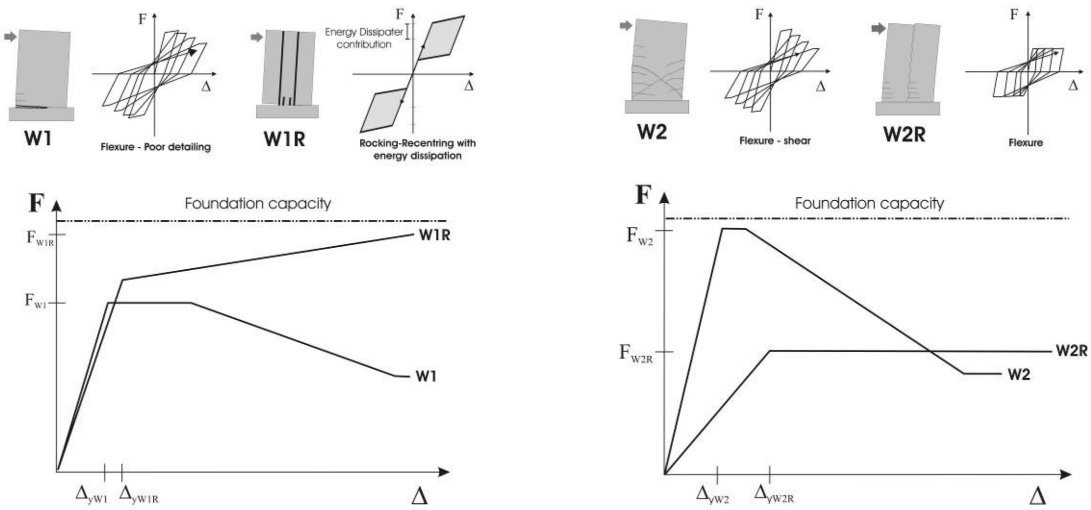
Figure 5: W2 geometry and reinforcement detailing



(a) (b) (c)

Figure 6: (a) W2R retrofit components; (b) Implementation of vertical cut; (c) Application of FRP

The expected behaviour of the benchmark and retrofitted walls is outlined in Figure 7. The general hysteretic form and the generalised monotonic force versus displacement response of the as-built and retrofitted walls is shown. Figure 7(a) compares the expected behaviour of W1 and W1R, whilst Figure 7(b) compares the expected behaviour of W2 and W2R.



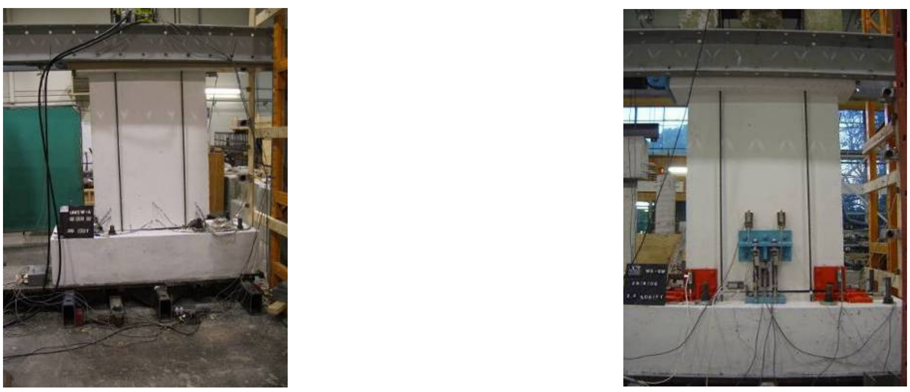
(a) (b)

Figure 7: Expected behaviour of the benchmark and retrofitted walls, (a) W1 and W1R; (b) W2 and W2R

4.1 W1 and W1R – Observations and Results

The observations and results of the experimental tests on W1 and W1R are discussed in this section. W1 was tested to a peak of 3.0% drift, with the behaviour governed by a single crack forming at the interface between the wall and foundation. The observed behaviour at peak response is shown in Figure 8(a). Additional characteristic of the behaviour were spalling and longitudinal reinforcement buckling at the toe regions of the wall, strength degradation in the hysteretic response after cycles to 1.5% drift and eventual longitudinal reinforcement rupture at the ends of the wall. The lap splice did not have any effect on the overall behaviour. The force versus displacement response for W1 is shown in Figure 9(a).

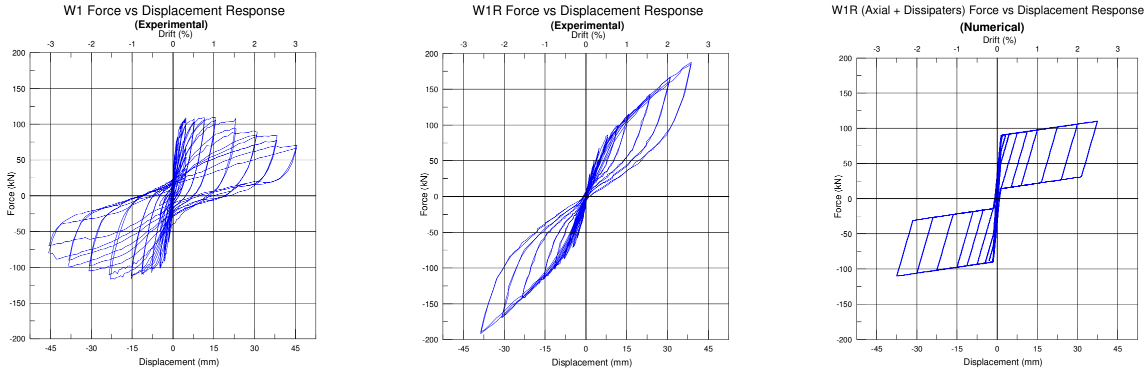
W1R was tested to a peak drift level of 2.5%. The wall at peak response is shown in Figure 8(b). The behaviour was governed by a single gap opening at the horizontal cut region and a self-centring behaviour was achieved with no crushing of the toe regions or cracks in the wall panel. The force versus displacement response for W1R is shown in Figure 9(b). A flag-shaped hysteresis was formed and there was only minimal stiffness loss as the test progressed and no strength degradation occurred. The peak strength of W1R was substantially higher than that of W1, which was required to ensure the peak displacements experienced during a seismic response would be comparable.



(a) (b)

Figure 8: Observed behaviour at peak response; (a) W1; (b) W1R

An alternative retrofit solution for W1R was numerically investigated and the force versus displacement response shown in Figure 9(c). This alternative retrofit solution represents a scenario similar to that outlined in Figure 2(b) as wall (c''). In this case the flexural capacity of the retrofitted wall is required to be less of equal to that of the as-built wall to ensure that the foundation capacity was not exceeded. The characteristics of a hybrid wall are still exhibited.



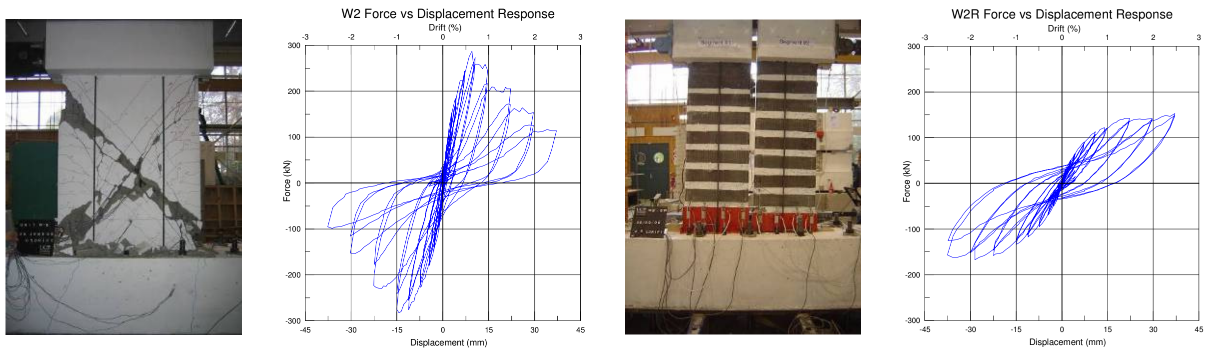
(a) (b) (c)

Figure 9: Force versus displacement response, (a) W1 (experimental); (b) W1R (experimental); (c) Numerical investigation of an alternative solution for W1R

4.2 W2 and W2R – Observations and Results

The observations and results from the experimental tests on W2 and W2R are discussed in this section. W2 was tested up to one cycle at 2.5% drift, after which testing was stopped as the wall was on the verge of collapse. The behaviour at the end of testing is shown in Figure 10(a). It was seen that diagonal tension (shear) cracks formed and extended from corner to corner across the wall panel in both loading directions. Excessive spalling was observed along the crack regions and the wall was deemed no longer capable of providing reliable gravity carrying capacity. The force versus displacement response for W2 is shown in Figure 10(b). It can be seen that after the 0.75% drift cycles severe strength degradation was observed and that on the final negative drift cycle to 2.5%, the strength was only 35% of the peak observed strength.

W2R was tested up to 2.5% drift, with a flexural inelastic mechanism observed. The behaviour at peak response can be seen in Figure 10(c), with the only damage being spalling at the toe region of the wall above the confinement armour and distributed cracking between the band of FRP. The spalling observed in the wall segment with the partially severed boundary element was substantially reduced, when compared to the other wall segment. The force versus displacement response for W2R is shown in Figure 10(d). It can be seen that a substantially more stable hysteresis was formed with a peak strength corresponding to 55% of the peak strength observed in W2. Reliable gravity carrying capacity was achieved whilst a substantial contribution to the lateral load resisting system was provided.



(a) (b) (c) (d)

Figure 10: (a) Observed behaviour W2; (b) Force versus displacement response W2; (c) Observed behaviour W2R; (d) Force versus displacement response W2R

5 CONCLUSIONS

The experimental tests discussed confirmed the feasibility and viability of using selective weakening techniques to improve the performance of structural walls. Conclusions drawn from the experimental investigations include:

- Selective weakening techniques offer a high level of control over the retrofitted behaviour of structural walls. They can be used to change inelastic mechanisms and the resulting strength can be higher or lower than the capacity of the as-built wall, depending on the retrofit aim. Lowering the capacity could be particularly useful in situations where the foundation has insufficient strength.
- The displacement capacity of an as-built wall can be improved by changing the inelastic mechanism from shear to flexure using selective weakening techniques.
- Selective weakening techniques can be used to introduce performance characteristics typical of new high performance jointed ductile seismic resisting systems (hybrid). These characteristics include a rocking re-centring behaviour that exhibits minimal damage after a seismic response.
- The retrofit solutions adopted in the experimental program were used for proof of concept purposes and still require refinement to solve cost-effectiveness and practicality issues. Consideration of the global effects, that the retrofit solutions have on the structure are also required.

Acknowledgements

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